The Ganges basin geometry records a pre-15 Ma isostatic rebound of Himalaya

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ABSTRACT

The Tertiary continental strata of the Himalayan foreland basin are subdivided in two groups, but the meaning of this subdivision was previously unclear. From the analysis of drill-holes, seismic lines, dated sections, field outcrops and balanced cross-sections, we find that the southward migration rate of the deposition pinch-out of the younger group is 19 ± 5 mm/yr and equals the Himalayan shortening rate. This equality shows that the flexural foreland basin development is mainly controlled by the motion of the thrust load. The long-term pinch-out migration rate was slower for the older syn-orogenic group. Erosion locally occurred at the end of its deposition, due to tectonic reactivation of lineaments of the Indian shield. We suggest that this change in the basin development is linked to the detachment of the subducted Indian lithosphere that decreased the slab pull and increased the mean compressive stress within the Indian plate, whereas the plate motion remained constant. The most important implication of our work is that the associated isostatic rebound could increase the Himalayan elevation prior 15 Ma.

Keywords: Himalaya, flexure, foreland basin, relief, slab break-off, tectonic reactivation.

INTRODUCTION

The timing of the rise of Himalaya is of great importance because Himalaya is the best example when trying to understand the relation between mountain belt tectonics and paleoclimate (Molnar et al., 1993; Zhisheng et al., 2001; Spicer et al., 2003). But this rise is highly debated, because there is no direct measurement of paleo-elevation. Therefore, geodynamical models that take into account the role of isostasy and horizontal stresses remain a powerful approach to deduce the relief evolution of a mountain belt (Molnar et al., 1993). In this paper, we hypothesize that the overall foreland basin geometry of the Ganga basin is controlled by flexural subsidence related to the neighbor Himalayan belt evolution. The basin geometry is used to specify the evolution of the stress that affected the Indian shield and to propose an evolution of the lithospheric root and relief of the Himalayan belt.

GEOLOGICAL SETTING

The Indian shield was affected by several tectonic events before the convergence of India toward Asia. Its northern part was strongly affected by the formation of a Proterozoic fold belt and the Proterozoic to Cambrian Vindhyan basin (Shukla and Chakravorty, 1994). Therefore, the crust beneath the Ganga basin (Fig. 1) is affected by inherited tectonic lineaments. These lineaments delineate from NW to SE a succession of spurs and depressions in the Tertiary Ganga basin (Raiverman et al., 1994) and are very oblique to the structural trend of the Himalayan thrust belt (Powers et al., 1998). This thrust belt induces a flexural subsidence that is the prime control of the foreland basin development (Burbank et al., 1996). The depotcenter was located close to the front of the collision belt (Fig. 2) and the sediment pinch-out migrated outwards (Lyon-Caen and Molnar, 1985) due to the motion of the thrust wedge (Huyghe et al., 2001).

Two groups define the syn-orogenic continental sediments of the foreland basin: the pre-Siwalik and the Siwalik group (Burbank et al., 1996; Najman et al., 2004). The lithostatigraphic distinction between the continental strata of the Pre-Siwalik and Siwalik group has been defined very early (Meddlicott, 1884), and the main distinction is the extent of the sedimentation domains. The base of the Siwalik group is at ca. 13 Ma in India (Najman et al., 2004) and older than 15.5 Ma in Nepal (Gautam and Fujiwara, 2000).

DEPOSITION PINCH-OUT MIGRATION RATE AND HIMALAYAN SHORTENING RATE DURING THE SIWALIK STAGE

A previous estimate of the pinch-out migration rate was obtained from 8 drill-holes (Lyon-Caen and Molnar, 1985). This result is revisited from a compilation of 26 drill-holes (Valdiya, 1980; Acharyya and Ray, 1982; Raiverman et al., 1994; Shukla and Chakravorty, 1994; Srinivasan and Khar, 1996; Bashial, 1998; Powers et al., 1998) and 5 outcrops of the Tertiary basal unconformity (Valdiya, 1980; Shresta and Sharma 1996; Sakai et al., 1999) (Table DR2[1]). Furthermore, 10 balanced cross-sections of the outer belt (Srivastava and Mitra, 1994; Srinivasan and Khar, 1996; Powers et al., 1998; Lavé and Avouac, 2000; Mishra, 2001; Mugnier et al., 2004) are used to estimate the displacement of the thrust sheets. The method of analysis is detailed in the Table DR2[1]. The Siwalik group is informally subdivided into lower, middle and upper lithostratigraphic units (Lyon-Caen and Molnar, 1985) and the age of the Siwalik units in the drill-holes is estimated from the nearest, amongst eleven, magnetostratigraphic studies (Fig. 1 and Table DR1[1]) (Burbank et al., 1996; Gautam and Rosler, 1999; Brozovic and Burbank, 2000; Gautam and Fujiwara, 2000). Nonetheless, these lithostratigraphic boundaries are diachronic at

[1] GSA Data Repository item 2004070. Table DR1, Age of the Tertiary lithostratigraphic units inferred from magnetostratigraphic studies and others methods, Table DR 2, The migration of the pinch-out of the Tertiary basin, and Table DR3, Shortening rate estimate through the central Himalaya.

local scale (Brozovic and Burbank, 2000; Huyghe et al., 2005) and along cross-sections transverse to the foreland basin (Lyon-Caen and Molnar, 1985). We take into account this diachronism to estimate the age uncertainty (see DR2[1]), leading to a smaller uncertainty to the pinch-outs located close to the dated sections.

We find that the pinch-out migration rate varies laterally for the Siwalik period. It is 19 ± 5 mm/yr in front of the central part of Himalaya and only 12 ± 3 mm/yr in the western part (Fig. 3). This lateral variation mimics the variation of the shortening rate: in central Himalaya, the shortening rate is 20 ± 5 mm/yr (De Celles et al., 2002; Mugnier et al., 2004) (Fig. 3, DR 3[1]), and in western part is 14 ± 4 mm/yr (Powers et al., 1998).

Our data sets are based on independent estimation procedures of the shortening and pinch-out migration rates and confirm their equality previously postulated by Lyon-Caen and Molnar (1985). Therefore our work reinforces the hypothesis that a flexural behavior of the lithospheric plate links the evolution of the Ganga basin to the translation of the Himalayan belt. Furthermore, the mean slope and the topography of the belt have probably not greatly changed since at least 15 Ma, because the Himalayan wedge migrates only if its taper is maintained (Dahlen and Barr, 1989).

THE EVOLUTION OF THE BASIN PRIOR TO THE SIWALIK DEPOSITION

The pre-Siwalik group is formed of continental strata with an age between 13 Ma and less than 30 Ma (Sakai et al., 1999; Najman et al., 2004). The pre-Siwalik basin is restricted to the very northern part of the Ganga plain (Raiverman et al., 1994), to the footwall of the basal décollement of the Sub-Himalaya zone (Powers et al., 1998) and to the top of few tectonic Himalayan slices (Najman et al., 2004). An “intermediate sequence” (Fig. 2A) beneath the Ganga basin was initially interpreted as part of the Tertiary group (Lyon-Caen and Molnar, 1985), but further works suggest that it consists of Vindhyan deposits (Srinivasan and Khar, 1996).

The southward migration rate of the pinch-out for the pre-Siwaliks (Fig.3) is smaller than the migration rate for the Siwaliks. We discuss in the following six different hypotheses to explain this change: 1) variation of the rigidity of the flexed plate (Waschbuch and Royden, 1992); 2) onset of a thrusting event (Fleming and Jordan, 1990); 3) internal thickening and narrowing of the thrust belt (Sinclair et al., 1991); 4) change in the shortening rate; 5) erosional unloading of the topographic wedge (Burbank, 1992); 6) lost of the heavy roots of the orogen (Sinclair, 1997).

A variation of the rigidity of the flexed plate is unlikely, because the rigidity was already great during the pre-Siwalik stage, due to the old (more than 500 Ma) thermotectonic age of the Indian lithosphere (Burov and Diament, 1995). Furthermore, flexural modelling of the Eocene-early Miocene foreland basin indicates a flexural rigidity greater than 7. 10^{23} Nm (De Celles et al., 1998), a value close to the present-day rigidity in central Himalaya (Lyon-Caen and Molnar, 1985).

EROSION AND TRANSPRESSION AT THE BASE OF THE SIWALIK GROUP

The fault activity evidenced beneath the foreland basin is used to test the others hypotheses proposed for the change of the migration rate.

Seismic data beneath the Ganga plain and the sub-Himalayan thrust belt (DMG, 1990; Shukla and Chakravorty,1994; Srinivisan and Khar, 1996; Raiverman et al., 1994) indicate that the partitioning of the Ganges basin in a succession of spurs and depressions is controlled by basement fault reactivation (Raiverman et al., 1994; Bashial, 1998). These spurs influenced the thickness and the southern depositional limits of the Pre-Siwalik group (Raiverman et al., 1994).

Locally, the south boundary of the upper sub-group is located to the north of the pinch-out of the underneath sub-group (Raiverman et al., 1994). This apparent backward migration is due to erosion that had removed the southern part of the upper sub-group (Fig. 2A and B) beneath unconformities (Fig. 2C) at the top of the Pre-Siwalik sub-group. This retrogradation causes the reduction of the long term pinch-out migration rate, though the “instantaneous” Eocene-early Miocene and late Miocene-Pliocene migration rate could be similar (De Celles et al., 1998).

These unconformities, though largely extended (Pascoe, 1964), are discontinuous laterally (Raiverman et al., 1994). The erosion seems mainly expressed above the basement faults and the complex pattern of the sedimentary bodies suggests a left-lateral transpressional tectonic regime along the lineaments oblique to the Himalayan trend. Normal faults, parallel to the Himalayan trend, throw down toward the north the base of the Tertiary strata (Raiverman et al., 1994) (Fig. 2B). They are related to the reactivation of Indian shield lineaments due to the negative curvature of the flexed lithosphere during the pre-Siwalik stage (Powers et al., 1998) and positive structural inversion (Gillcrist et al., 1987) leads to basement folding at their hanging-wall at the end of the pre-Siwalik stage. Therefore, a phase of fault reactivation is synchroneous with local erosion or deposition of the uppermost pre-Siwalik sequence and predates 15.5 Ma in Nepal and 13 Ma in India. This phase was linked to an increase of the mean horizontal forces applied by the plate motion close to the orogen area and/or a decrease of the bending moment that controls the curvature of a flexed plate.

FLEXURE OF THE INDIAN PLATE: THE ROLE OF THE CRUSTAL LOADING OF THE THRUST WEDGE VERSUS LITHOSPHERIC SLAB BREAK-OFF

Onset of a thrusting event and internal thickening of the thrust belt would change the geometry of the crustal thrust wedge (Fleming and Jordan, 1990; Sinclair et al., 1991), leading to a retrogradation of the pinch-out and also an increase of the curvature of the flexed lithosphere. Such a curvature increase stage does not match to a stress increase, and we therefore exclude these hypotheses for the transition between pre-Siwalik and Siwalik stage.

Shortening rate during the pre-Siwalik stage is 20 ± 8 mm/yr (Fig. 3). Choosing the lower value of 12-14 mm/yr would keep equal shortening rate and migration rate. Therefore, an increase of the shortening at the end of the pre-Siwalik stage would explain the stress increase. We nonetheless do not favour this interpretation because it is associated with a constant convergence between India and Eurasia (DeMets et al., 1990) and an increasing erosion of Himalaya (Clift et al., 2004; Bernet et al., 2005).

This regional increase of the erosion could drive an erosional unloading (Burbank, 1992) at the Siwalik/pre-Siwalik transition. Nonetheless, erosional unloading would imply that erosion exceeded the volume of rocks moved by tectonics above the Indian plate. A lower bound for the rate of tectonic loading is the product of the lower estimate of the shortening (12 mm/yr) by the lower estimate of the thrust thickness (20 km). Therefore the erosion would have to exceed 240 m^3/yr for a swath of 1 m, or 0.5 km^3/yr for the whole Himalaya, i.e., to be as great as the Plio-Quaternary erosion estimated by Métivier et al. (1999). No data suggests such a regional peak of erosion by that time.

We rather suggest that a lithospheric slab break-off increased the relief and consequently the erosion. This slab break-off increased the stresses within the Indian plate through two processes: a) The loss of the mantle lithospheric roots decreases the additional forces exerted at the trailing edge of the flexed lithosphere (Lyon-Caen and Molnar, 1985) and decreases the curvature of the plate; b) The loss of the continental mantle lithospheric roots increases the mean horizontal deviatoric forces applied by the orogen area and surrounding lowlands to one another

(Molnar et al., 1993). Tomographic analysis (Van der Voo et al., 1999) suggests that several detached portions of the lithospheric mantle are located beneath Tibet and Himalaya, due to a delamination of the Indian continental mantle and its break-off. Such a break-off (Fig. 4) fits with the Neogene magmatic evolution of Southern Tibet (Mahéo et al., 2002). We suggest, from the timing of the fault reactivation beneath the foreland basin, that the break-off was achieved before 15.5 Ma in Central Himalaya and progressively propagated westward over several millions years.

Numerical models (Buiter et al., 2002) indicate that the break-off related-uplift zone is much larger than an uplift zone at the hanging-wall of any mega thrust fault (Beaumont et al., 2001), but it is much smaller than the width of Tibet. The Tibetan uplift is probably linked to several processes, and the slab break-off could be one of them. It induced a kilometer-scale increase of the altitude of the very southern part of the Tibetan plateau and led to topographic emergence of a discrete Himalaya belt with respect to Tibetan plateau prior to 15 Ma.

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Figure 1. Structural sketch of the Himalaya and its foreland basin. *Cu*—Magnetostratigraphic studies of the Tertiary units (see Table DR1[1]). • Dr—Drill holes (or outcrops) of the base of the Tertiary sediments (see Table DR2[1]). 1—Himalaya. 2—sub-Himalaya. 3—foreland basin. 4—Indian shield. 5—Linaments beneath the Ganga foreland basin from Raiverman et al. (1994) and Srinivasan and Khar (1996). 6—Main Himalayan Thrusts. 7— Pinch-out of the pre-Siwalik group from DMG (1990), Shresta and Sharma (1996), Srinivasan and Khar (1996) and Raiverman et al. (1994). 8— Southern edge line of the basin from Lyon-Caen and Molnar (1985).

Figure 2. Cross-sections through the Tertiary sediments. The vertical scale is magnified by 5. A: Cross-section through the foreland basin. Ages refer to the pinch-out: 1—Siwalik group; 2—Tertiary pre-Siwalik group; 3—Pre-Tertiary sequences. BF—Reactivation of an Indian shield lineament. Northern part of the Tertiary basin from Raiverman et al. (1994) and southern part

from Shukla and Chakravorty (1994); intermediate sequence from Srinivasan and Khar (1996), basement structures from Shukla and Chakravorty (1994). B: Structure of the Tertiary sediments beneath the sub-Himalayan belt of Dehra-Dun area from Raiverman et al. (1994) and Powers et al. (1998). MFT: Main Frontal Thrust; MBT: Main Boundary Thrust. Same scale for cross-section A and B. The thickness of pre-Siwalik sediments greatly varies close to the Mohand drill-hole. C: Zoom of a seismic profile (Location on Fig. 2B). Beneath the sub-Himalayan belt, toplaps occur beneath an unconformity at the base of the Siwaliks. Paleo-relief is preserved beneath the lower Siwaliks at the hanging-wall of steep faults. These faults are cut and transported by the basal décollement of the sub-Himalayan zone.

Figure 3. A plot of the age of the base of the Tertiary sediments versus the distance from the edge of the Ganges basin. Circles, squares, continuous and hached lines refer respectively to drill-holes east of E78° and west of E78°, and to the cross-section of Figure 2B (see Table DR2[1]). The thick × refer to a plot of time versus Himalayan shortening (see Table DR3[1]) and the hatched line is a linear fit for these data.

Figure 4. A sketch of the Ganges basin-Himalaya-Tibet evolution. The vertical scale is magnified by 5 for the uppermost crust (shallower than 10 km) to see the foreland basin and the Himalayan relief. The lithospheric structures are not vertically magnified. 1—Tertiary foreland basin; 2—Crust of the Indian shield; 3—Himalaya; 4—Tibetan Zone; 5—Indian lithospheric mantle. MFT: Main Frontal Thrust; MCT: Main Central Thrust. A: Geometry at ca. 20 Ma. B: Geometry at ca. 15 Ma. Lithospheric mantle break-off induced (1) an increase of the stresses and (2) fault reactivation in the Indian shield, (3) local erosion of the foreland basin, (4) increase of

the altitude of the Himalaya (uplift profile adapted from Buiter et al.; 2002), and (5) volcanism in southern Tibet. C: Present day state.

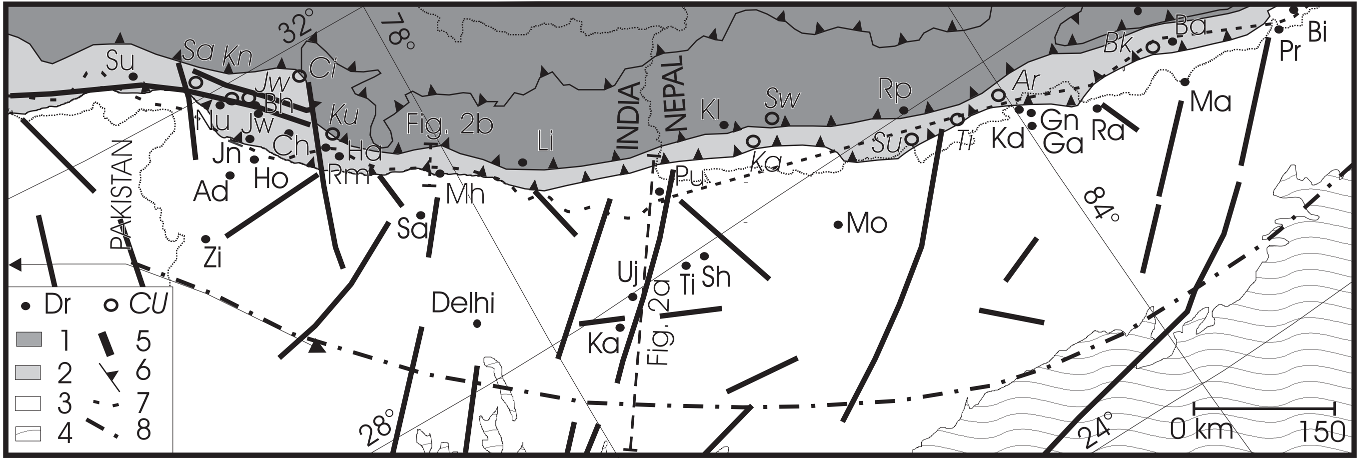
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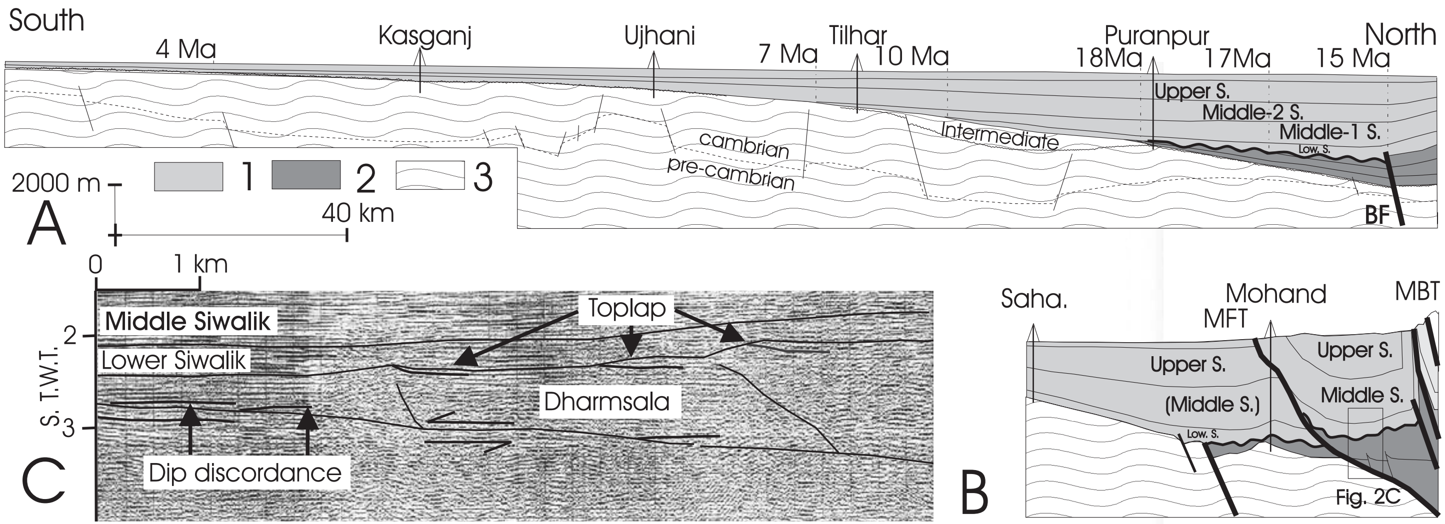
Fig.1

FIG. 2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15 Ma
North
Upper S.
Middle-2 S.
Middle-1 S.
Low. S.
Intermediate
cambrian
pre-cambrian
2000 m
1
2
3
40 km
BF
A
0
1 km
Middle Siwalik
Lower Siwalik
Toplap
Dharmsala
2
3
S. T.W.T.
Dip discordance
C
Saha.
Mohand
MBT
MFT
Upper S.
Upper S.
(Middle S.)
Middle S.
Low. S.
Fig. 2C
B

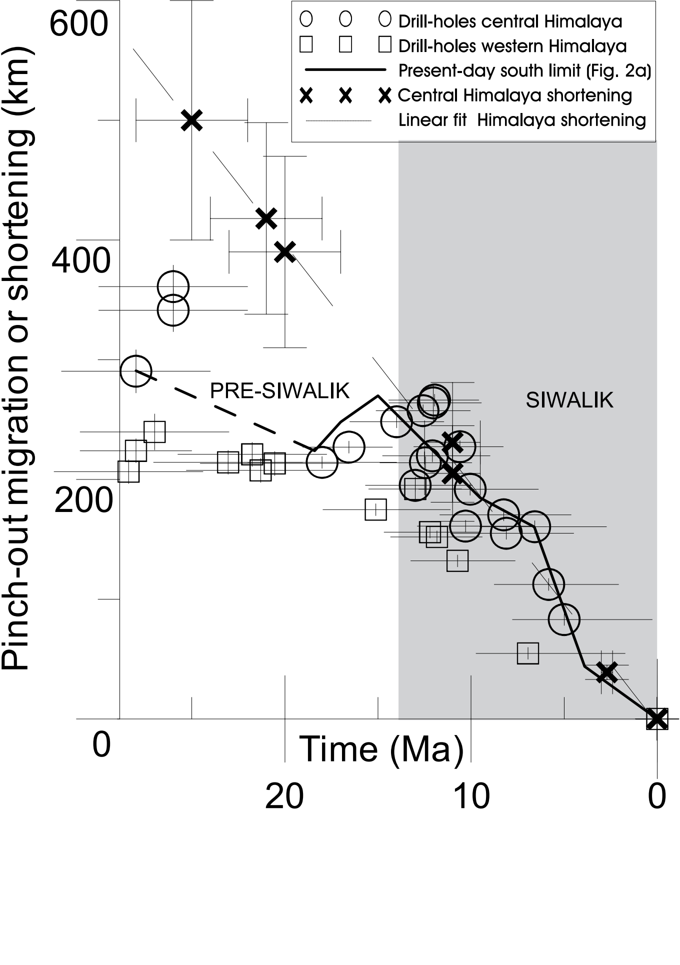
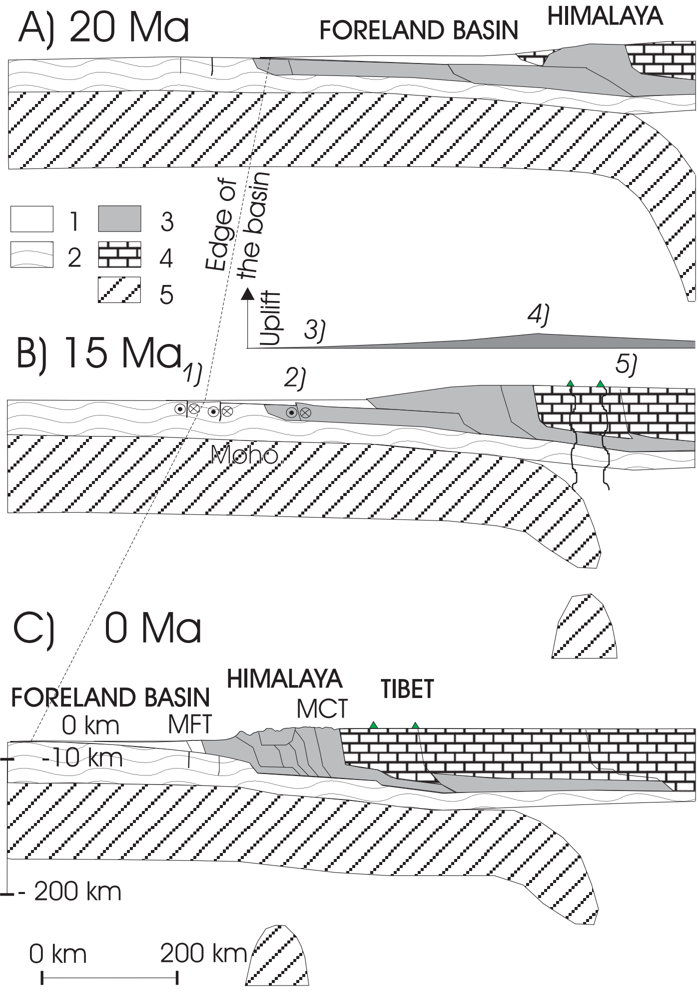

Drill-holes central Himalaya
Drill-holes western Himalaya
Present-day south limit (Fig. 2a)
Central Himalaya shortening
Linear fit Himalaya shortening
Pinch-out migration or shortening (km)
600
400
200
0
PRE-SIWALIK
SIWALIK
Time (Ma)
20
10
0

Fig. 3



A) 20 Ma
FORELAND BASIN
HIMALAYA
Edge of the basin
1
2
3
4
5
Uplift
3)
4)
B) 15 Ma
1)
2)
5)
Moho
C) 0 Ma
FORELAND BASIN
HIMALAYA
MCT
TIBET
0 km
MFT
-10 km
- 200 km
0 km
200 km

Fig.4